1   Title:

2   Bioenergy with Carbon Capture and Storage (BECCS): Consequential lifecycle assessment
3   (cLCA) to inform UK net zero climate policy

4

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13

14   **Keywords:**

15   BECCS, bioenergy, climate, forest, carbon, LCA

16   **Key policy insights:**

17   ➢   Sustainability criteria currently applied to biomass in a UK BECCS system could result in
18   a less beneficial climate compared to a non-BECCS based counterfactual over Paris
19   Agreement relevant timescales.

20   ➢   Understanding carbon forest dynamics is key when considering time-bound targets such
21   as the UK's net zero by 2050.

22   ➢   When feedstock demand drives additional forest harvests, near-term climate policy is
23   unlikely to achieve beneficial results.

24   ➢   Carbon capture and sequestration (CCS) is unlikely to improve non-CCS bioenergy
25   climate impacts.

26   **Running Head:**

27   cLCA for BECCS

28   **Social Media Promotion**

29   For forest based bioenergy systems, forest carbon dynamics are key when considering climate
30   impacts. When relying on additional harvests, climate benefits are unlikely. Carbon capture and
31   sequestration (CCS) is unlikely to improve climate impacts significantly

32   **Social Media Handle**

33   BECCS bioenergy forest

34

35 **Abstract**

36 Bioenergy with carbon capture and storage (BECCS) is a prominent carbon removal technology
37 in mainstream climate modelling, assumed to produce negative greenhouse gas (GHG)
38 emissions by capturing and storing CO_2 released when wood is combusted. This analysis
39 explores the appropriateness of UK climate policy with reference to future introduction of
40 BECCS. It compares the BECCS pathway based on current pellet sourcing with a
41 counterfactual without BECCS, with foregone electricity provided from elsewhere in the UK grid.
42 The analysis updates the consequential life cycle assessment (cLCA) for a UK bioenergy plant
43 using wood pellets from three mills in the Southern US (Buchholz et al., 2021).

44 Compared to a non-bioenergy scenario, the earlier LCA showed that the demand for wood
45 pellets induced by the UK bioenergy plant led to reduced forest carbon stocks in managed pine
46 forests in Louisiana and Mississippi for at least 40 years. This led to increased GHG emissions
47 in the bioenergy scenario even when grid emissions replaced by bioenergy are considered.

48 We consider CCS technology becoming fully operational in electricity generation from 2030 with
49 90% carbon capture rate. Results indicate that the proposed UK BECCS system sourcing
50 pellets from the southeastern US would not result in short to medium term benefits compared
51 with a non-BECCS system until around 2053. The GHG emission impact of the CCS technology
52 itself is less significant than the impact of wood pellet sourcing on forest carbon stocks and
53 flows. Thus, current biomass sustainability criteria focusing on stable or increasing forest
54 productivity or carbon stocks do not capture the important time dependence of the system
55 including forest carbon dynamics.

56 We demonstrate the importance of LCA approaches that address the system-wide value chain
57 of GHG emissions and sequestration compared to realistic counterfactual scenarios – i.e. what
58 would have happened in the absence of the intervention. We conclude that a dynamic approach
59 to forest carbon stocks and flows should be applied in policymaking – particularly in relation to
60 time-bound targets such as those supporting the Paris Agreement. This study focuses solely on
61 the GHG emissions related to BECCS implementation; not addressing wider social and
62 environmental concerns.

1 INTRODUCTION

1.1 UK Climate Policy and BECCS

The 2008 Climate Change Act is the primary UK legislation that provides the framework for climate change mitigation, including a legally binding target to reduce greenhouse gas emissions to net zero by 2050.

The Act also created the Climate Change Committee (CCC) who advise on UK carbon budgets and monitor progress against them. In their Seventh Carbon Budget (CCC, 2025) covering the period 2038 to 2042, the CCC indicates that by then engineered removals will need to be operating at scale, increasing from zero in 2030 to 8.7 million metric tonnes CO_2e in 2040 and 9.6 million metric tonnes CO_2e in 2050. Most of these engineered removals would come from Bioenergy with Carbon Capture and Sequestration (BECCS) technology with Direct Air Carbon Capture and Storage also contributing (CCC, 2025). The Department for Energy Security & Net Zero (DESNZ) is the UK government body that has responsibility for setting biomass sustainability criteria. In its 2023 Biomass Strategy (DESNZ, 2023a) it described its intent to strengthen sustainability criteria for biomass use and assess the potential of BECCS applications and noted strong stakeholder support for monitoring, reporting and verification that adopts a whole systems approach to sustainability.

Of particular relevance to this study is a DESNZ report on the ability of BECCS to deliver negative emissions (DESNZ, 2023b) noting BECCS is sometimes considered a *'controversial'* reduction pathway because of concerns over its ability to deliver removals. They echoed stakeholder concern that the mechanisms used in the UK to demonstrate biomass is sustainably sourced and, of particular relevance to this study, noted '[…] *it is also vital to understand how changes in monitored forest carbon stocks are related to evolving management practices*.' DESNZ referenced the use of sustainable criteria based on the criterion of stable or increasing forest carbon stocks (for example SBP, 2023), recognizing that in the near to medium term, the bulk of forest biomass will come from existing managed forests in North America (and that BECCS deployment in the UK will mainly use this source).

Other UK Government bodies also address biomass and BECCS issues, for example the Committee of Public Accounts (CPA) who, in 2025, reported on the Government's support for biomass (HC CPA, 2025); stating that DESNZ '*has relied for too long on an untested regime for making sure that biomass is from genuinely sustainable sources'* also expressing concern about carbon accounting systems that underpinning the current supply of biomass.

The report of the Subsidy Advice Unit (SAU; UK CMA, 25) as part of the Competition and Markets Authority is also relevant to near term BECCS policy, providing advice to DESNZ on the proposed (and subsequently approved) subsidy for Drax Power Ltd and its large scale current unabated bioenergy plants over the period 2027 – 2031. In addition to strengthening security of supply the SAU also considered the DESNZ assessment around conversion of existing biomass power plants to CCS and in particular that the absence of the subsidy would jeopardize BECCS deployment and plans for negative emissions.

In December 2025 the UK Government published a consultation document proposing a common biomass sustainability framework with the overall policy objective of ensuring government only supports biomass that supports its net zero objectives – maximizing carbon

105 benefits from bioenergy use (UK Government, 2025). It proposes building on existing criteria to
106 explicitly require that long term forest carbon stocks are stable or increasing.

107 Our BECCS study criteria are designed to relate to developments described above, specifically
108 linking to the impact of changed forest management practice in the USA on overall forest
109 carbon stocks, the subsequent impact on greenhouse gas emissions and ultimately
110 achievement of time-bound UK climate goals. While UK policy does not specifically endorse
111 any single project or provider, documents such as those from the SAU (UK CMA, 25) and the
112 DESNZ sponsored independent review of greenhouse gas removal approaches (Whitehead,
113 2025) clearly acknowledge the conversion of the existing bioenergy plant operated by Drax as a
114 leading contender for delivering BECCS negative emissions. Drax's bioenergy plant, converted
115 from coal, currently provides around 5% of UK electricity generation (Drax Global, 2025). Our
116 BECCS scenario accordingly focuses on the conversion of the existing UK bioenergy plant,
117 including associated pellet supply chains from the USA.

118

1.2 BECCS and LCA

120 A key attribute of BECCS, from a policy perspective, is its ability to deliver negative emissions. It
121 then follows that robust accounting for emissions is a critical consideration. A '*stunning gap*'
122 has however been identified between the large number of studies showing the need for
123 negative emission technologies (such as BECCS) to achieve the Paris Agreement's goals and
124 the status of research, development, and deployment of the technologies (Torvanger, 2019).

125 Studies have shown that BECCS, depending on the conditions of its deployment, could lead to
126 either carbon positive or negative emissions over a project lifetime with 'profound implications
127 for the policy frameworks required to incentivise and regulate the widespread deployment of
128 BECCS technology' (Fajardy and Dowell, 2017). For example, a recent review of the negative
129 emissions potential of BECCS cited 13 power plant studies, two of which showed positive
130 emissions, while other studies showed a range of negative emissions of −2180 g/kWh to −479
131 g/kWh (Wang et al., 2024). An LCA applied to BECCS accordingly poses many challenges, not
132 least in accounting for the time dependent nature of forest-based carbon stocks, its location,
133 specific characteristics and the interaction of BECCS with other systems such as power (where
134 alternatives to BECCS generated power need to be considered) and forest products
135 (complementary to biomass including paper and timber products; Giasson et al., 2023; Yao and
136 Zhang, 2025). It is therefore challenging to compare results from different studies due to
137 differences in goals, system boundaries, methodology applied, and assumptions made (Krogh
138 et al., 2024; Salas et al., 2024).

139 Accordingly, a simple inventory based (attributional) LCA is increasingly viewed as inappropriate
140 for informing decisions around negative emissions technologies (Brander et al.,2021). Instead, a
141 consequential LCA (cLCA) approach that seeks to identify the environmental consequences of
142 a decision or a proposed change is more appropriate. Brander et al. (2021) also indicates the
143 importance of the time dependence of emissions/removals across the BECCS value chain,
144 referencing the UK 2050 net zero target as an example of needing to deliver negative emissions
145 within a specific timeframe.

146 The factors described above have informed the design of this study (building on earlier work by
147 Buchholz et al., 2021). While earlier BECCS studies tended to focus on the potential of the CCS

148 technology itself (García-Freites et al., 2021), Whitehead (2025) provided a recent UK oriented
149 DESNZ sponsored review of greenhouse gas removal approaches and considered feedstock
150 constraints, rather than physical infrastructure, to be the primary constraint on future BECCS
151 implementation. Our study accordingly takes a whole system perspective.

152 In order to inform the potential for a BECCS system to deliver system-wide benefits compared
153 to a counterfactual the following features have been included:

154 ➢ Focusing the scope on UK activity given its legally mandated deadline for net zero and
155 its identification of the potential role of BECCS in achieving this goal;

156 ➢ Align with likely BECCS implementation scenario involving conversion of existing large
157 scale (currently unabated) UK bioenergy plants;

158 ➢ Region specific forest carbon stock and flow modelling aligned to current and planned
159 sourcing of biomass for future BECCS implementation;

160 ➢ Inclusion of other forest products in the modelling to reflect the full scope of forest
161 carbon flow in the source area;

162 ➢ Inclusion of emissions from other means of electricity production;

163 ➢ Assumptions introduced that would tend to favour the BECCS over the non-BECCS
164 pathway including early uptake of BECCS (by 2030) with high levels of capture (CCS at
165 90%) and a 2025 emissions factor for the non-BECCS counterfactual, which would
166 accordingly involve some conventional fossil fuel generation and neglect planned
167 electricity system decarbonisation.

168 Our reasoning for utilizing BECCS favorable assumptions is to reflect a best case test on the
169 capability of achieving relative long term benefit over the non-BECCS counterfactual. Buchholz
170 et al. (2021) represents a robust cLCA approach that is already available and relevant to the
171 study and its findings provide insight into current UK climate policy, particularly if the results are
172 viewed in the context of a precautionary approach that properly considers (as per the Paris
173 Agreement) the impacts on both emissions and sinks. The recent UK Government consultation
174 (UK Gov, 2025) on sustainable biomass also touches on this issue, indicating that when
175 considering accounting for negative emissions biomass related policies should assess whether
176 to exclude life cycle stages that constitute negative emissions from methodologies if they
177 determine that *a more conservative approach, which does not allow for the accounting of
178 negative emissions in the LCA, is more appropriate in their specific regulatory or environmental
179 context'*. Buchholz et al. (2021) outcomes are also consistent with studies in other ecosystems
180 linking the increase in biomass demand with additional harvests (Buchholz et al., 2019), and
181 only long-term climate benefits (if any) of bioenergy systems relying on additional harvests
182 (Brown et al., 2024; Giasson et al., 2023; Walker et al., 2013; Schlamadinger et al., 1995); bar
183 the absence of stochastic events such as wildfire, insects outbreaks, drought, or storms.

184 Undoubtedly, changing key assumptions would affect, for example, the parity period; at which
185 initial net GHG emissions that might initially be higher for a bioenergy scenario than the
186 baseline scenario (carbon debt) is 'paid back' (Schlamadinger et al., 1995; Mitchell et al., 2012).
187 For example, use of combined heat and power (CHP) could significantly improve the GHG

188 profile of the bioenergy scenario, as would reductions achieved in logistics and transport (see
189 section 4.2 Policy recommendations). Conversely, improvement in UK electricity grid GHG
190 conversion factors beyond the 2025 figure employed in the study, delays in CCS
191 implementation and lower GHG removal efficiencies would all serve to disfavour the bioenergy
192 scenario. It is very likely the grid average used in this study is conservative given its ongoing
193 projected reduction, further favouring the baseline and extending the parity point further into the
194 future. Our BECCS scenario also reflects that the largest export market for US wood pellets is
195 the UK (approximately 70% for 2023; USDA, 2024) and that Drax sources around 80% of its
196 pellet feedstock from the US (Drax Group plc, 2024); mostly sourced in the southeastern US. A
197 significant part (16% of total Drax consumption)[1] of these pellets are sourced in just three Drax-
198 owned pellet plants in Louisiana and Mississippi: Amite, Lasalle, and Morehouse. Combined,
199 these pellet mills source around 71% of its feedstock from non-industrial private loblolly pine
200 plantations in form of pulpgrade roundwood and 29% from sawmill residues (referenced below
201 as the 'study feedstock').[2]

202

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[1] Assuming a total of 7.6 million metric dry tonnes of feedstock (Drax Group plc, 2024) and a pellet production efficiency of 87% (Buchholz et al., 2021)

[2] Amite and Morehouse: 20% sawmill residues; Lasalle: 50% sawmill residues; with the remainder sourced from pine roundwood.

2 METHODS

2.1 Key methods adopted from Buchholz et al. (2021)

2.1.1 LCA accounting framework

The methodology for this analysis has used the same scenario assumptions, input data and model outputs for forest-related carbon cycling as well as the wood pellet supply chain documented in Buchholz et al. (2021); this time with CCS added to the bioenergy power plant from 2030.

The approach is consistent with the GHG Protocol's pilot Land Sector and Removals Guidance (WRI and WBCD, 2022), which states, on evaluating the impact of major business decisions, that actors should consider 'avoided removals (removals that would have otherwise happened, but that, as a result of a company's activities, did not happen),' *and use 'intervention accounting methods… [to] assess the GHG impacts of an action compared to the conditions most likely to occur in the absence of the action. Companies should use the results to ensure that actions lead to global net GHG benefits.'*[3]

Identical to Buchholz et al. (2021), this study employed a cLCA that considered the climate impact of the study feedstock when consumed at electricity facilities in the UK. 'A cLCA *gives an estimate of how the global environmental burdens are affected by the production and use of the product'* unlike an attributional LCA that '*estimates what share of the global environmental burdens belongs to a product*' (Ekvall, 2019).

A key element to consider under any LCA accounting is that 'decisions within an LCA are preferably based on natural science.' (ISO, 2006a). In other words, biophysical modeling needs to take full precedence over economic modeling to meet ISO standards. Contrary to points raised by, e.g., Sohngen et al. (2025) and Sohngen (2024), the primacy of biophysical over economic modeling is further supported by the fact that biophysical realities (e.g., tree-level growth along with intra-tree competition) will underlie any already considerable uncertainties for LCA outcome and the attribution of increased forest carbon stocks due to economic activity might be questionable the first place (Searchinger et al., 2025). These uncertainties will further expand when adding economic modeling algorithms on e.g., anticipated market effects (see, e.g., Favero et al., 2023a, 2023b, 2020), that are in large part anchored onto simplified and stand-level growth dynamics (Fuller et al., 2025).

We followed rigorous and project-appropriate LCA boundary setting and accounting standards (ISO, 2006a, 2006b)[4]; balancing standard accounting principles of relevance, completeness, consistency, accuracy, transparence, and conservativeness; scaled to the specific task[5]. Buchholz et al. (2021) analysis therefore comprised carbon and GHG flows (i) in the forest, (ii) during product processing and transport for all products and post-use for both short-lived (such as pellets) and durable wood products, and (iii) avoided electricity generation emissions from fossil fuels for electricity generation in the UK.

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[3] Pilot guidance is subject to change before finalization.
[4] Along with relevant amendments and standards such as (ISO, 2020a, 2020b, 2019, 2018)
[5] For forest-related LCA related case studies; see e.g., Buchholz et al. (2022, 2014) and Marland et al., (2013)

240 Buchholz et al. (2021) explain that, besides accounting for processing, transporting, and grid
241 related GHG emissions and any change in anticipated durable wood product manufacturing and
242 consumption, '*in the case of the Drax pellet mills, this requires integrating the anticipated*
243 *change of carbon stocks in the forest under a bioenergy demand scenario compared to a*
244 *baseline scenario without demand. Only when the combined effects of both avoided electricity-*
245 *generation GHG emissions and landscape carbon fluxes including processing GHG emissions*
246 *are accounted for, can a GHG emission parity point be established*.' The parity point has been
247 proven to be a temporally sensitive metric in the context of bioenergy climate impact analysis
248 (Schlamadinger et al., 1995; Mitchell et al., 2012; Walker et al., 2013; Ter-Mikaelian et al.,
249 2015).

250

2.1.2 Understanding the impact of biomass utilization on forest carbon cycles and forest management assumptions

253 Detecting change due to additional biomass utilization to feed bioenergy systems through
254 carbon stock monitoring is fraught with challenges around landscape-level signal detection as
255 well as attribution (e.g., Peng et al., 2023). In most cases, model-based scenario analysis is the
256 best suited approach for cLCA to understand general climate-relevant implications of landscape
257 policy choices (Haight et al., 2020), i.e., bioenergy policy. Furthermore, in order to yield relevant
258 results, a case-specific identification of sourcing locations is key to identify landscape-level
259 carbon impacts that might be missed based on broad scale assumptions such as, e.g., grouping
260 all private timberland within sourcing distance to a pellet mill (Aguilar et al., 2022) when biomass
261 is mostly sourced from one particular land owner type such as small private timberlands with
262 heterogenous management contexts (Silver et al., 2015). This also applies to consistent choices
263 of boundary selection and impact categories (Salas et al., 2024; Wang et al., 2024).

264 Buchholz et al. (2021) consulted regional experts to verify plausible 'baseline' and plausible
265 'bioenergy' scenarios to form the forest carbon stock basis. Based on the insight that the
266 studied pellet mills primarily sourced pulpgrade biomass from non-industrial pine plantations,
267 the baseline scenario assumed that the 2.8 million ha of non-industrial private forest
268 surrounding the pellet mills would continue to be actively managed, with a clearcuts at 25 years
269 followed by replanting with pines. In the 'bioenergy' scenario, additional thinning was modelled
270 to occur at year 15 with no change to the other forest management aspects. This change in
271 forest management for the 'bioenergy' scenario was based on the insight that the pellet mills'
272 demand for pulpwood grade biomass triggered otherwise nonprofitable thinnings that would
273 have been forfeited in the absence of the pellet demand. Growth and harvest simulations were
274 run using the US Department for Agriculture Forest Service's Forest Vegetation Simulator's
275 Southern Variant (FVS-SN; USFS, 2020) while carbon stocks and GHG fluxes due to changes
276 in the durable wood product categories where modeled mostly based on Smith et al. (2006).

277 A 2025 UK grid emission profile for electricity generation was used to substitute for bioenergy in
278 the baseline scenario. This factor included a proportion of fossil fuel powered generation and is
279 likely favorable to the bioenergy scenario as the actual grid factor is expected to continue on a
280 downward emissions trajectory from 2025 to 2030 and beyond.

281

2.2 BECCS relevant methodology

In addition to all methods presented in Buchholz et al. (2021), we assumed for the bioenergy scenario (BECCS scenario) that BECCS would become fully operational in 2030 (Table 1) and compared results with a baseline with no bioenergy production (non-BECCS scenario). This assumption is more optimistic than current CCC carbon budget implications (we have assumed that the CCS system would be i) added to all four power units and ii) be operational from 2030). We assumed a 90% capture and permanent storage of the CO_2 from the power station flue gas (e.g., Brandl et al., 2021) whereas the achieved value may be around 76% (Quiggin, 2021). We also assumed that 27.5% of the electricity output of the plant is used to power the carbon capture technology itself as Drax Group plc reported on a 11% drop from an initial 40% electric conversion efficiency to the UK Parliament (Drax Group plc, 2021). We also assumed that the biomass power plant would compensate for this shortfall by increasing its sourcing of wood pellets in order to maintain a consistent amount of electricity output. Therefore, we assumed that the 27.5% net electricity drop would be compensated by an increase in output from the same sourcing region and strategy (pulpgrade roundwood from non-industrial pine plantations as described in Buchholz et al. 2021) and continue post CCS implementation. We assumed that the wood basket would be enlarged while the sawmill residue supply would remain constant. Stand conditions in the enlarged wood basket were assumed to be identical to the original wood basket with the sawmill residue volume remaining constant.

The resulting analysis therefore shows how the GHG balance over time differs for a BECCS and a non-BECCS scenario. For the non-BECCS scenario, we employed an GHG emission profile of 0.146 metric tonnes CO_2e/MWh based on the official UK electricity grid emission target for 2025 (UK Committee on Climate Change, 2015).

Table 1: BECCS-relevant data inputs to augment Buchholz et al. (2021).

Variable	Unit	Input	Comments and sources
CCS start year	Calendar year	2030	Full CCS production in all four Drax units
CCS energy use	% of initial electric conversion rate	27.5 %	15-29% (BECCS Stockholm, 2022) Drax specific: 11% drop from initial 40% net electric conversion efficiency (Drax Group plc, 2021)
CO_2 stack emissions captured	% of CO_2 emissions captured	90%	90%-98% (Brandl et al., 2021; Fajardy et al., 2021; Pisciotta et al., 2022)
CO_2 storage leakage	% of initially stored CO_2	0%	

3 RESULTS

3.1 BECCS relevant results

Even with CCS technology fully operational from 2030 at the UK power station, the BECCS scenario demonstrates a less favorable whole system climate outcome than the non-BECCS scenario. Our analysis finds that fueling the BECCS system with the study feedstock would not provide GHG benefits within the relevant GHG policy window considering the CCC carbon budget timeline.

Although 90% of the CO_2 emissions from wood pellet combustion are assumed captured at the power station starting 2030, the reality of a long-term parity point is in the first case attributed to thinning forests to meet wood pellet demand for UK BECCS. These additional thinnings, compared to a no-bioenergy scenario, result not only in an initial carbon stock loss but also in a reduced capacity for the forests to remove carbon from the atmosphere until around 2053. In comparison, Buchholz et al. (2021) did not find any GHG benefits realized for the study feedstock mix before 2059 when not including a CCS component to the bioenergy system.

While all scenarios (non-BECCS, non-CCS bioenergy from Buchholz et al. (2021), BECCS) do show a long-term trend to increase forest carbon stocks over time, the BECCS scenario continues to maintain lower forest carbon stocks than the baseline scenario due to the higher thinning rate for approximately 20 years, whether wood pellet inputs are increased or substitute electricity generation in the UK is included to counteract the BECCS energy penalty. While individual trees typically show an increased growth rate following a thinning, net primary productivity and therefore carbon sequestration for the entire stand decreases – at least for several decades (Buchholz et al., 2021).

The analysis found that the time taken to reach emissions parity with the baseline no-BECCS scenario (i.e. the time when atmospheric carbon in each scenario would equalize in a given year) would take until around 2053 (Figure 1). Only after that time would BECCS produce additional 'negative emissions' compared to the baseline, due to the need to 'pay back' the GHG gap created between 2030-2053.

Figure 1 compares the carbon balance in both the BECCS and no-bioenergy/BECCS scenarios over time. It demonstrates that the bioenergy/BECCS scenario generates higher net emissions than the no-bioenergy/BECCS scenario until around 2053. Figure 1b shows the difference between the BECCS and no-bioenergy/BECCS scenarios, with the no-bioenergy/BECCS baseline scenario zeroed for ease of comparison. The space between the lines up to the parity point shows the cumulative difference in atmospheric carbon of 1,148 million metric tonnes CO_2e between scenarios during the timescale analyzed (Figure 1b, greyed out area). Since we only analyzed the climate impact of pellets derived from the three Drax pellet plants mentioned above, this result reflects the impact of 16% of Drax' scale by pellet volume input. Whether this is representative of the wider global supply base of Drax would need to be established by an understanding of the forest carbon dynamics in each specific sourcing area but is most likely indicative of any sourcing strategy that includes additional harvests (Cabiyo et al., 2025; Giasson et al., 2023; Schlamadinger et al., 1995). The implications of this gap for UK Net Zero commitments are outlined in the Policy recommendations below.
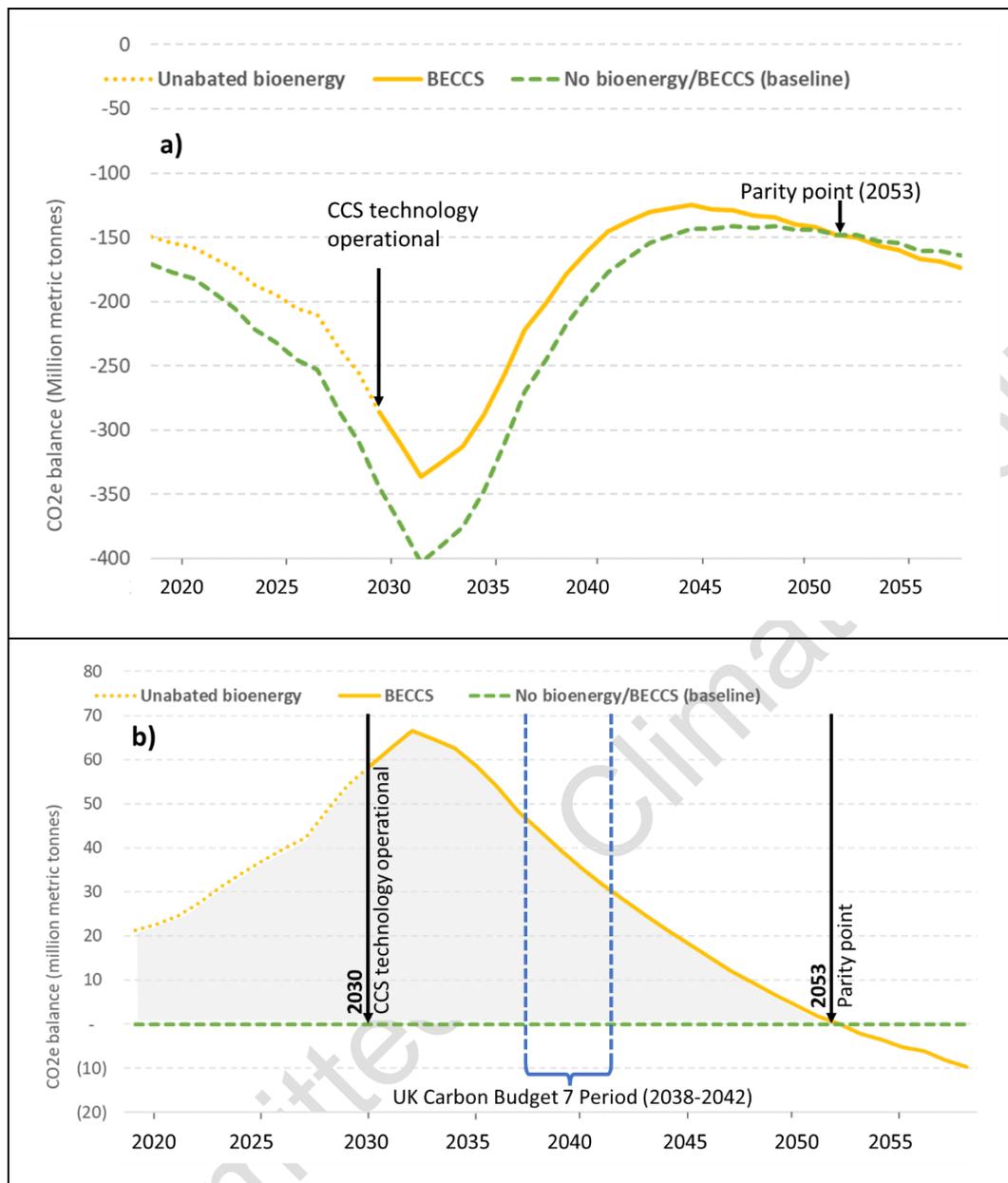
350 Figure 1: Net carbon impact of BECCS and no-BECCS when the biomass power plant increases its
351 sourcing of wood pellets in order to maintain a consistent amount of generation. Results presented in
352 actual GHG fluxes (a) and with the baseline no-BECCS scenario converted to zero (b).

353

3.2 Sensitivity to key model assumptions

The results are highly sensitive to assumptions regarding CCS capture and storage rates. If the CCS capture rate drops from 90% to below 79%, as estimated by Quiggin (2021), the parity point for the entire BECCS system is not achieved within the next 33 years, i.e., not before 2058. This relationship likely applies equally to the CCS storage (or leakage) rate, which this study assumes to be 100% (i.e., permanent storage and 0% leakage). This means that even a slow release of a fraction of the stored carbon over time would therefore have considerable (adverse) impact on the parity time.

In contrast, the BECCS system is less sensitive to the internal electricity demand driven by the CCS system (i.e., energy use). If the internal electricity supply required to run the CCS system is improving from 27.5% to 15% of total net electricity production, the parity point is still not achieved within the next 30 years.

We also explored an alternative where the drop in net electricity production would not be compensated by an increased production of electricity at the bioenergy plant and thus an increase in forest harvesting. In this scenario we assumed that the net electricity produced by the biomass power plant drops by 27.5% and is compensated by other sources of generation in the UK, based on a fixed 2025 projected UK grid conversion factor (GHG per unit of electricity generated). The pellet supply remains unchanged compared to Buchholz et al. (2021). Similarly to the results presented above, this scenario did not reach parity until around 2052. The major difference was the absolute volume of CO2 sequestration in both BECCS and no-BECCS scenarios. By increasing the amount of wood pellets produced and burned, more forest area experiencing increased harvest volumes is included in the cLCA and therefore more carbon flows are accounted for. Overall, the carbon balance remains favorable towards a no-BECCS scenario.

Using the 2025 grid emission factor as a counterfactual for both the BECCS and non-BECCS scenario is another key assumption for bioenergy cLCAs. It is not only highly likely that the average grid emissions will experience a dynamic shift towards lower emission rates over time (Macintosh et al., 2015) which would push the parity point between the BECCS and non-BECCS scenarios further out. At the same time, the average grid emission profile is limited in its applicability to bioelectricity systems that can generate on-demand power and therefore might be better compared to other electricity generating sources associated with higher-than-average GHG emission profiles but with the same on-demand attributes such as natural gas. However, even in the field of on-demand power sources, low GHG-emission systems such as battery storage provide a fast-paced development towards larger scales and lower per-unit costs (Tong et al., 2020). Backup or standby generation capacity based on biomass or natural gas will need to compete financially with this rapid development. At the same time, the current use of bioenergy in the UK grid does not match the profile of backup power production but provides constant base power.

393 # 4 DISCUSSION AND RECOMMENDATIONS

394 ## 4.1 Forest carbon stocks dominate GHG fluxes

395 Figure 2 represents a single year perspective (2021) of carbon stocks in the sourcing forest
396 area and the related flows of carbon. The net sequestration is the difference between carbon
397 captured by the forest from the atmosphere and forest related emissions, e.g., from tree
398 mortality. The first observation is that a full picture of both emissions and sinks should consider
399 and quantify all the significant flows, including wood products. The large size (relative to other
400 flows) of the forest carbon stocks and the sequestration emphasize the importance of forest
401 management compared to the bioenergy related emissions – a proportionally small change to
402 forest management practice and associated flows is therefore likely to be significant to the
403 overall carbon balance. It is also worth noting that the forest carbon stocks in the sourcing
404 region will experience a decline post 2030 due to imbalanced forest age cohorts - independent
405 of bioenergy harvests (see Supplementary Information).

406
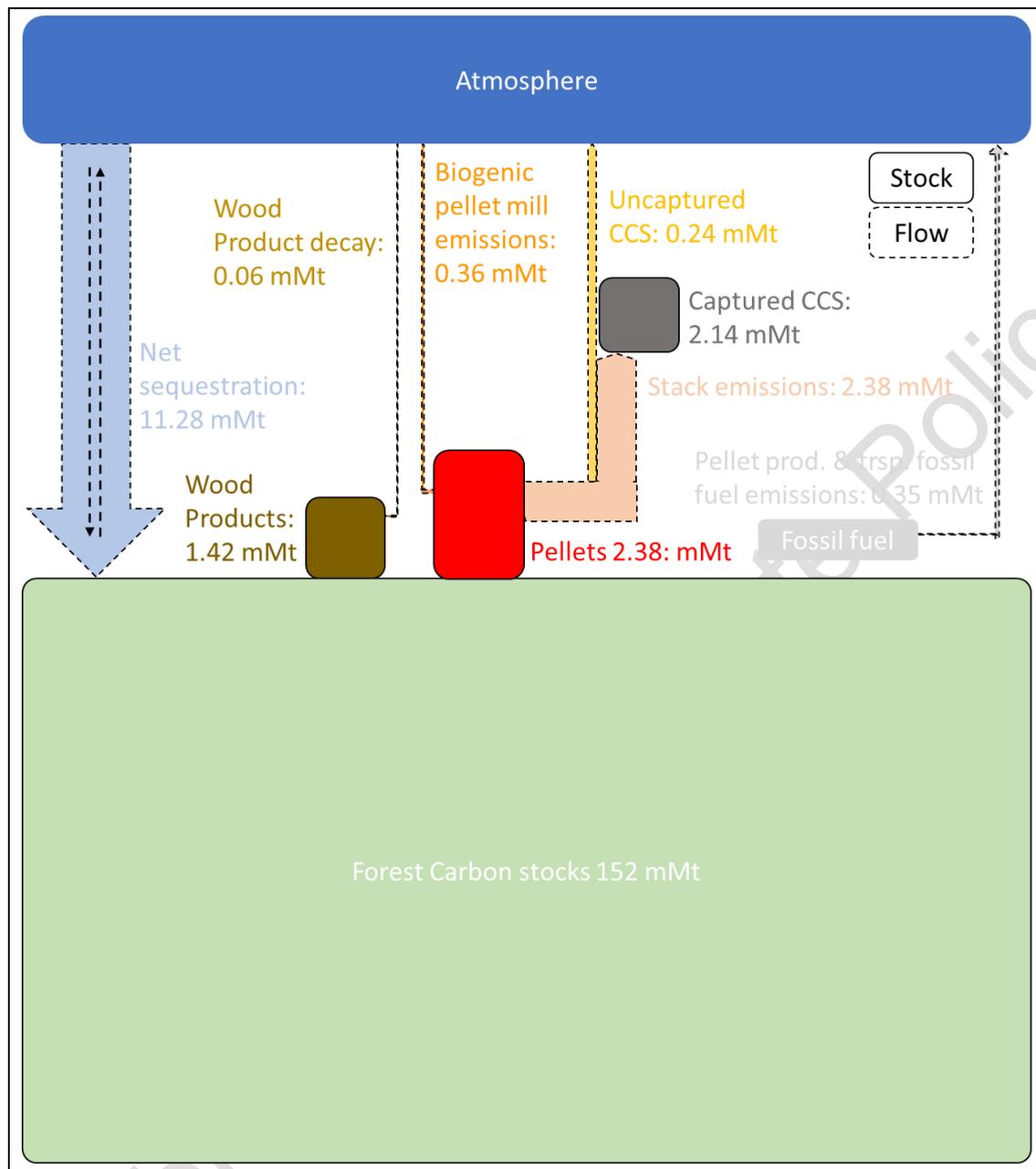
Figure 2: Single year (2021) carbon stocks and flows under the BECCS scenario. Units in million metric tonnes of CO2e (mMt). Stocks are depicted with solid boundaries while flows are shown with dotted boundaries. cLCA results for forest-based bioenergy systems are dominated by forest carbon stock (change). Surface area approximately corresponds to volume of annual stocks and flows. Net sequestration (light blue, 11.28 mMt CO2e) flows towards forest stocks (green, 152 mMt CO2e). Annual wood products (dark brown, 1.42 mMt) production is associated with 0.06 mMt from product disposal/decay (light brown). The 2.38 mMt of carbon temporarily stored in wood pellets (red) are associated with 0.36 mMt biogenic emissions (orange) and 0.35 mMt fossil fuel emissions (light grey) from the pellet production and transportation process. When the pellets are combusted, an additional 2.38 mMt is emitted (salmon), with an assumption that 90% or 2.14 mMt is captured by CCS (dark grey) and 10% or 0.24 mMt is uncaptured/released (yellow). Atmosphere and fossil fuel stocks depicted without boundary since these are open stocks. Study feedstock provides around 16% of total Drax supply.

4.2 Policy recommendations

This cLCA study uses data that represents current forest conditions and models that provide projections forward over time. Several variables have been deliberately chosen to be more favorable to the BECCS pathway in order to provide, essentially, a type of stress test for policy decisions. These choices should enable an exploration of what circumstances might need to be met in order to favour a BECCS scenario over something like a business-as-usual practice and they should also to reflect the potential uncertainty associated with the methodology. It may well be beneficial from a climate policy perspective to include such an approach in decision making – exploring under what circumstances an intervention becomes unfavourable.

In this cLCA analysis, which is spatially focused and intended to inform UK policy targets, electricity generation from wood pellets does not provide optimal climate benefits if pellet markets trigger harvest activities that would not have occurred in the absence of increased pellet demand, even if CCS is installed to remove stack emissions. It emphasizes the importance of considering the full value chain of both emissions and removals including forest related sequestration that might be achieved in a counterfactual scenario (even if regional forest carbon stocks are currently increasing in the presence of a biomass market/extraction of pellet feedstock). The most appropriate forest management strategy will be highly dependent on local conditions including, but not restricted to forest management, and considerations of such should be applied to all areas from which there is significant sourcing. Moreover, the dynamic nature of forest carbon stocks and flows necessitate a dynamic approach to assessing the policy implications of BECCS which might extend to near term targets such as those expressed in UK carbon budgets or longer-term aspirations around net zero.

In advocating for a systems based cLCA utilising counterfactuals to enable effective policy decision making this study aligns with other published work including DESNZ (2023b) in applicability and resonates in methodology and outcomes for other forest ecosystems (Brown et al., 2024; Cabiyo et al., 2025; Giasson et al., 2023; Schlamadinger et al., 1995; Walker et al., 2013). It also underscores the challenges and widespread assumptions that CCS provides near term climate benefits in science (Cabiyo et al., 2025) and policy (Calvin et al., 2023).

DESNZ (2023b) specifically focuses on carbon dynamics including when management is changed to increase supply in forests that are already supplying wood products. It notes that '*A growing market for bioenergy such as wood pellets is likely to have variable effects on forest management and carbon stocks in forests. On the one hand, it may encourage more extensive and frequent thinning of stands, which is likely to diminish the total carbon stocks across the affected forest landscape. On the other hand, markets for bioenergy can enhance the value of small trees, boosting the economic value of forest stands, thereby encouraging landowners to retain their existing forests, instead of converting them to other more lucrative land uses (such as growing crops), which would lead to an even more significant loss of carbon stocks.*' In relation to the essentially static measure of constant/increasing forest carbon stocks it concludes '*Hence, the impact of the increasing rate of biomass supply on forest carbon stocks cannot be inferred simply from the fact that the carbon stocks are increasing*'; citing earlier published work such as that of Dale et al. (2017) as '*partial evidence that forest management could be positively influencing forest carbon stocks*'.

The recent UK biomass consultation (UK Government, 2025) proposes an explicit requirement building on existing criteria such as SBP (2023) that long term forest carbon stocks are stable or enhancing, at the same time stating that '*Changes in forest management can have negative*

464 *carbon impacts even if forest carbon stocks are stable. This is because changes in*
465 *management can result in the forest carbon stock being lower than it would have been if the*
466 *management changes had not occurred.*' (noting that they had not seen 'robust evidence' of
467 long-term carbon stock impact due to management changes). Their statement nonetheless
468 aligns with the findings of our study.

469 The Giasson et al. (2023) study is also particularly relevant to understanding how different forest
470 management strategies influence emissions and why a dynamic approach should be taken to
471 policy decisions. Seven management strategies were modelled, all of which gave a net carbon
472 sink over the 95-year simulation period. The different strategies however did show differing
473 emissions pathways over time with the most intensive management approach (involving
474 increased harvest and increased partial cut) having higher emissions (compared to a business-
475 as-usual counterfactual) over a 20–50-year timescale which would be relevant, for example, to
476 UK and Paris Agreement aligned targets.

477 Cabiyo et al. (2025) have published a comparable cLCA study exploring Southeastern US
478 emissions and landscape carbon changes with scenarios considering a range of biomass end
479 use applications including local BECCS. Consistent with our study they identify policy related
480 concerns about the use of the stable/increasing forest carbon stocks criterion, identifying it as
481 *'likely to be insufficient in many cases'* for carbon accounting purposes. An important difference
482 compared to our approach is that Cabiyo et al. explore potential market responses to projected
483 future increases in demand for biomass. They project biomass facilities sourcing from a wider
484 area and also land use change as natural forests and agricultural land are converted into pine
485 plantations. Differences in local electricity grid conversion factors are also significant. Their
486 chosen grid intensity factor of 336 gCO_2e/kWh is more than double our UK figure of 0.146
487 metric tonnes CO_2e/MWh; reflecting the more emissions intensive generation in the
488 Southeastern US. The impact of displacing higher emissions electricity generation is to reduce
489 the parity time (compared to a non-BECCS scenario). Though wholly inappropriate for a UK
490 generated electricity scenario, applying a grid emission factor as high as in Cabiyo et al. (2025)
491 would not shift the parity period to the near term in a policy context, reducing the parity time
492 from 2053 to 2046.

493 The DESNZ sponsored independent review (Whitehead, 2025) acknowledged the likelihood of
494 UK BECCS implementation utilising the retrofitting of CCS to existing unabated biomass plant
495 and its reliance on existing feedstock supply chains (as we described in our study). This led to
496 one of Whitehead's key recommendations that the UK should seek to minimise dependence on
497 imported wood pellets, as global demand increases. They highlighted concerns including land
498 use change and deforestation. On the basis of our study, we would also add whole value chain
499 GHG emissions related to changes in forest management practice to the argument for domestic
500 UK biomass sourcing.

501 In summary we believe that more attention needs to be paid to the forest management stage of
502 the overall BECCS system than has been apparent in much contemporary policy decision
503 making. It should be regarded as a sink that can be affected in different ways, particularly when
504 there are changes to forest management practice. This would involve taking a dynamic
505 modelling approach that goes beyond current practice of relying on measures of
506 stable/increasing forest carbon stocks. This is particularly important when thinking in policy
507 terms about time bound net zero targets and reflected in the Paris Agreement itself in Articles 4
508 and 5 which describe achieving a balance between anthropogenic emissions and removals by

509 sinks (UN, 2015). Article 4 states that '*In order to achieve the long-term temperature goal set*
510 *out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions **as soon as***
511 ***possible** [bold font added] […] so as to achieve a balance between anthropogenic emissions by*
512 *sources and removals by sinks of greenhouse gases in the second half of this century […]*'.
513 Noting the '*as soon as possible*' element, Article 5 furthermore indicates that action should be
514 taken '*to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases*';
515 specifically referencing forests.

516 This analysis demonstrates the importance of addressing the full value chain of carbon stocks
517 and flows of an intervention, compared with a 'baseline' counterfactual scenario, if the
518 intervention were absent.

519 This updated LCA analysis suggests that a UK BECCS system based on wood pellet supply
520 from three Drax pellet mills in the Southern US would increase, rather than decrease, levels of
521 atmospheric CO_2e compared to a scenario without BECCS demand, until around 2053.

522 The cumulative additional atmospheric CO_2e in the BECCS scenario compared to the non-
523 BECCS scenario over the Carbon Budget 7 period 2038-2042 is equivalent to almost a third
524 (30%) of the entire budget limit over this period (Burnett, 2025). This is currently invisible to UK
525 carbon accounts. The IPCC have indicated, with very high confidence, that near term reduction
526 of emissions '*would reduce projected losses and damages for humans and ecosystems*' (Calvin
527 et al., 2023).

528 Table 2 below showing CCC projected UK carbon budgets also emphasizes the importance of
529 near-term emission reduction along the pathway to 2050 in order to meet policy requirements.

530 Given the urgency to meet near-term emissions budgets to avert climate tipping points,
531 underlined by the Paris Agreement, policymakers should consider the near-term carbon impact
532 of their interventions relative to counterfactuals. In this analysis, UK BECCS from existing wood
533 pellet supply regions does not provide short- to medium-term climate benefits, despite its
534 prominence in Net Zero plans.

535 This analysis underlines the importance of assessing counterfactuals for climate policy choices.
536 It is only when comparing the BECCS scenario to a counterfactual pathway without BECCS that
537 the relative impact on the overall carbon balance is apparent.

538 Governments and institutions should undertake and adopt a full value chain LCA approach in
539 order to accurately make a full carbon account of interventions which aim to reduce atmospheric
540 carbon.

541 All stakeholders should continue to monitor the investment implications of evolving sustainability
542 standards and GHG accounting and disclosure, for example via the GHG Protocol, as updates
543 may reveal that currently prominent technologies or supply chains are higher carbon than
544 previously believed.

545

546 Table 2: Projected emissions implied by pathway against current and future carbon budgets (based on:
547 HM Government, 2021; Burnett, 2025).

Years	Carbon budget 3	Carbon budget 4	Carbon budget 5	Carbon budget 6	Carbon budget 7
Million metric tonnes CO2e limit (annual equivalent)	2,544 (509)	1,950 (390)	1,725 (365)	965 (193)	535 (107) proposed
Percentage reduction on 1990 (implied for carbon budgets)	41%	55%	60%	78%	87% (proposed 2040)

548

4.3 Technical considerations and next steps in relevant LCA accounting methods

551 Sourcing biomass for energy applications from forests that show a decline in forest carbon
552 stocks does not necessarily relate to unfavorable bioenergy-induced climate impacts. Nor does
553 sourcing from forests with stable or increasing forest carbon stocks necessarily indicate
554 favorable impacts. Sustainability standards or assessment methods that solely rely on stable
555 carbon stocks over time (e.g. SBP, 2023) are limited in their meaningfulness. It is important to
556 consider if the actual impact of biomass harvests increases or decreases carbon sequestration
557 rates in the source region. This needs to also include the impact of stochastic events on carbon
558 stocks and sequestration rates such as wildfire or drought. Sourcing biomass through forest
559 restoration activities in wildfire prone regions is a primary example (Buchholz et al., 2022;
560 Johnston et al., 2026). However, this restoration biomass tends to be more expensive to source
561 as it is more dispersed, often located in remote and inaccessible terrain, and bulky (small
562 diameter stems, tops, limbs).

563 This study further underscores that while CCS can improve GHG benefits, the associated
564 additional energy requirements result in only limited improvements from a climate perspective
565 and need to be carefully evaluated on a case-by-case basis and a focus on boundary setting
566 (Salas et al., 2024; Wang et al., 2024). To align with ISO LCA standards and minimize
567 uncertainty, the inclusion of economic modeling for GHG LCA should be very limited in its scope
568 for any LCA (Fuller et al., 2025; Peng et al., 2023; Searchinger et al., 2025).

569 From a technology perspective, bioenergy providing climate benefits can be achieved when
570 feedstock sourcing results in lower landscape GHG emissions (e.g., Johnston et al., 2026) or
571 used in high-efficiency CHP applications (Isler-Kaya et al., 2025). In contrast, adding feedstocks
572 associated with low GHG emission profiles such as sawmill residues (Alizadeh et al., 2023),
573 even at considerable rates, is unlikely to compensate for negative GHG impacts associated with
574 biomass from additional harvests. Efficient use of bioenergy is also a key factor. For instance,
575 and contrary to a CCS addition, identifying opportunities where excess heat can be used to
576 offset can make even feedstocks associated with a long-term parity point a near-term policy
577 opportunity. If excess heat would be used and replace natural gas for e.g., industrial process
578 heat or residential heating in addition to electricity production, the parity point of the study
579 feedstock would shift from > 2058 to around 2038. However, identifying heat demand at the
580 scale of converted coal power units is challenging and points towards distributed CHP systems
581 (Isler-Kaya et al., 2025); ideally scaled to local heat demand, e.g., natural gas applications.

582 To further improve accounting methods, two areas of further development stand out in terms of
583 improving temporal aspects of GHGs including i) GHG emission discounting (Scott et al., 2023;
584 Sproul et al., 2019; Timmons et al., 2016) as well as ii) actual atmospheric GHG residence
585 times (dynamic LCA; Levasseur et al., 2010). A careful choice of the LCA framework and
586 further research in LCA accounting methodologies are warranted.

587

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592

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1   # SUPPLEMENTARY INFORMATION

2   ## 2021 Study results

3   Figure SI3 shows the changing levels of forest carbon stocks (million metric tonnes CO2e) in
4   both the baseline and bioenergy scenario over the modelled period. It can be seen here that
5   there are higher forest carbon stocks in the baseline compared to the bioenergy (additional
6   thinning) scenario. This difference is maintained throughout the modelled period, albeit there is
7   some convergence, particularly in the 2030s. In both cases the forest carbon stocks are
8   increasing up to around 2030 and as such might be treated as equivalent under a regime that
9   only uses carbon neutrality of feedstock and/or stable or increasing forest carbon stocks as a
10 primary sustainability criterion. The decline in modelled forest carbon stocks in the 2030s up to
11 around 2045 reflects an imbalance in age cohorts as many stands mature. The change in
12 carbon stored in durable wood products from a no-bioenergy/no thinning to bioenergy/thinning
13 scenario was insignificant.

14
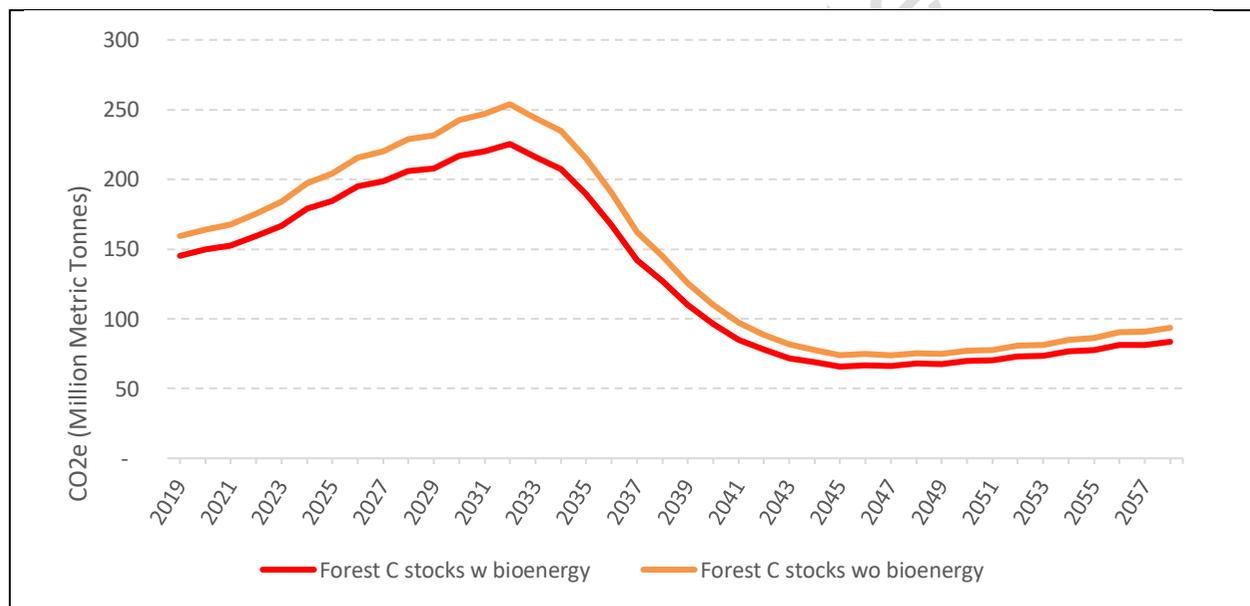
15 Figure SI3: Forest stocks in the woodshed as a five-year rolling average.

16

17 Extending the LCA from the forest stock level to include treatment of wood products and
18 utilization of pellets to generate electricity in the UK (bioenergy scenario) and a counterfactual
19 (baseline) which incorporates wood products and generation of electricity in the UK using a
20 predicted 2025 grid average gives an overall carbon position over time of BECCS and non-
21 BECCS scenario. The baseline scenario can be seen to be overall more favorable from a GHG
22 perspective until around 2050 (the parity point is where the two lines on the graph coincide)
23 even allowing for the contribution to the bioenergy scenario made by ongoing CCS stack GHG
24 emission removal after 2030. It is clear that from a carbon/Net Zero perspective that the
25 baseline scenario is more favorable, particularly as the overall benefits are felt earlier

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